CALAMVS GLADIO FORTIOR
1858

Numerical Simulation of Projectile Acceleration Process Using Solid/Gas Two-Phase Reacting Flow Model

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ystems Utilizing Solid Propellant

Chemical energy of solid propellant
≒ 4MJ/kg

→

Kinetic energy of projectile

Gun System

Military Technology

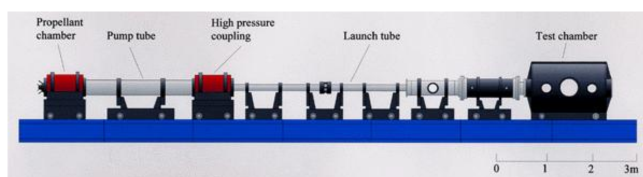
Cannon

http://www.army-technology.com/projects/crusader/crusader5.html

Scientific Research

Ballistic Range

http://www.knlab.msl.titech.ac.jp/



http://ceres.ifs.tohoku.ac.jp/~coe/jfacility.html

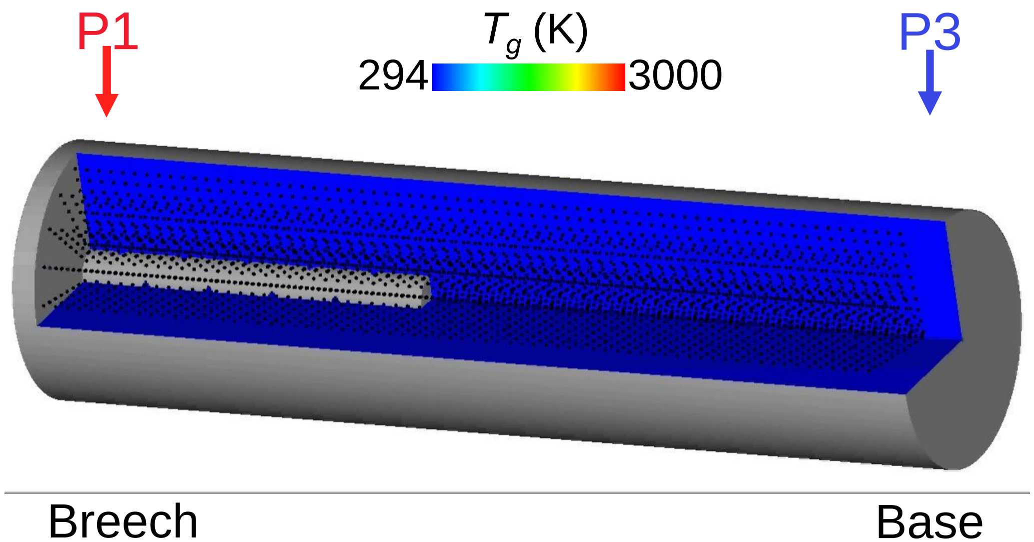
Solid Rocket

Space Propulsion

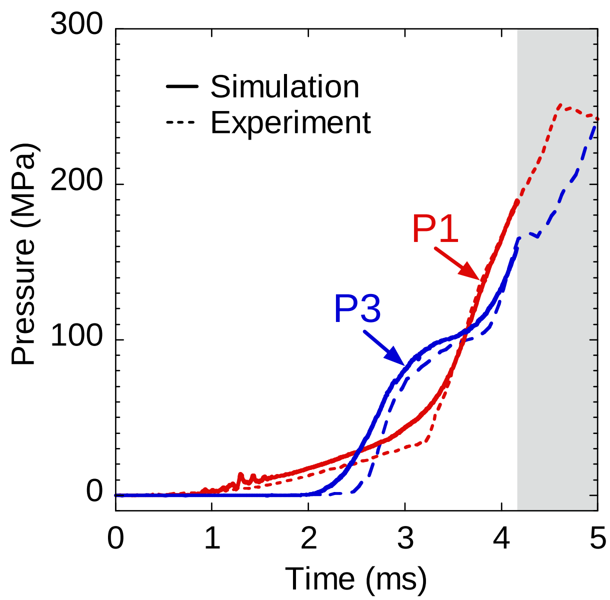
Solid Rocket Booster

http://spaceinfo.jaxa.jp/db/kaihatu/shuttle/shuttle_g/sts-87-2.jpg

ssure of Granular Solid Propellant



Typical Propellant Chamber



H. Miura *et al.*, ISEM2008

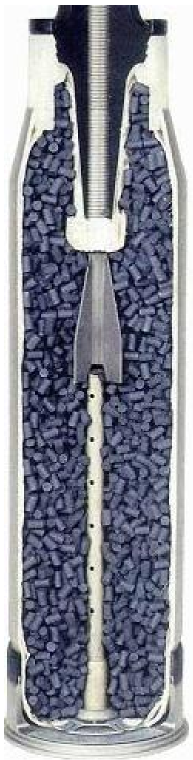
The movement of granular solid propellant causes the chamber pressure fluctuations.

↓

Simulation of propellant grains movement is significant to predict the destructive pressure waves generation.

bular Solid Propellant

Granular propellant



FAS Military Analysis Network

Characteristics of granular propellant

ÅLarger surface area

Ÿ Rapid fire

ÅEasy adjustment for propellant mass

ÅProblem of strong pressure waves

Tubular propellant

Characteristics of tubular propellant

ÅSmaller surface area

Ÿ Slow burning

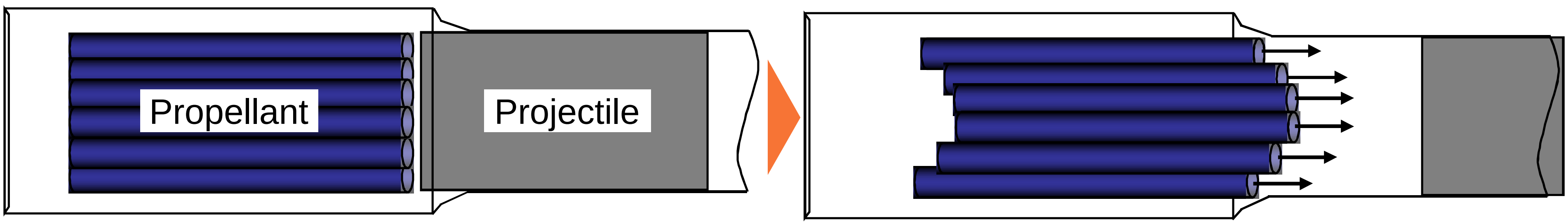
ÅUniform ignition and uniform charge concentration

Simulation technique for tubular propellant combustion should be developed.

Modeling for tubular propellant movement with burning

n of Tubular Solid Propellant

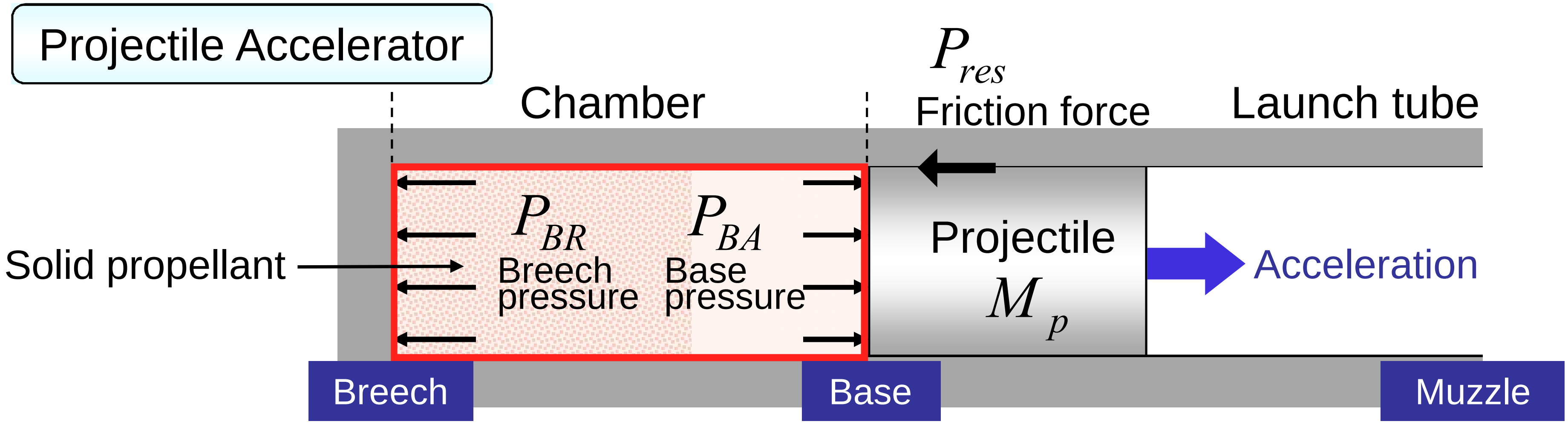
To simulate tubular propellant behavior in the chamber



Modeling for tubular propellant movement with burning

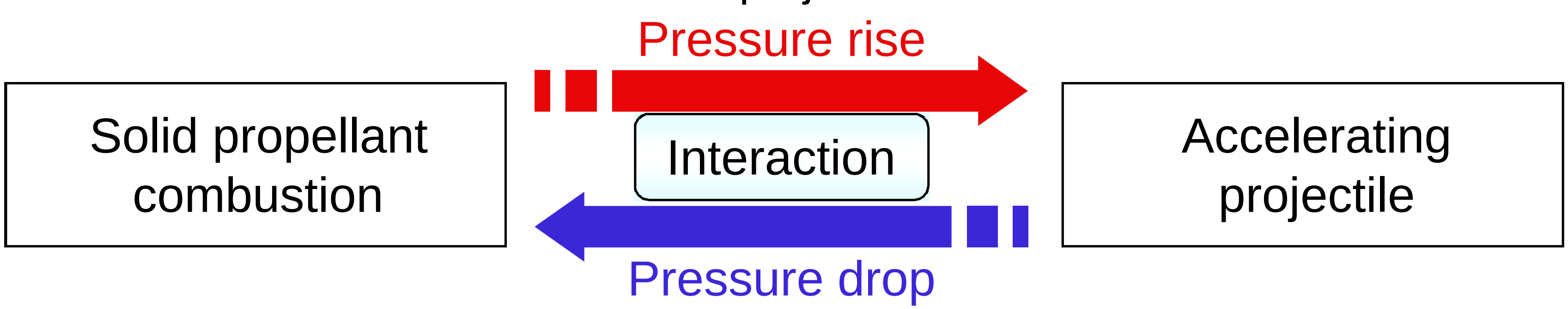
- ❑ A long tubular propellant lies in the wide range of computational domain.
  - Ÿ Consideration of property distributions on propellant surface
- ❑ Each tubular propellant moves in the chamber.
  - Ÿ Movement model for propellants by Lagrangian approach

…n for Projectile Accelerator



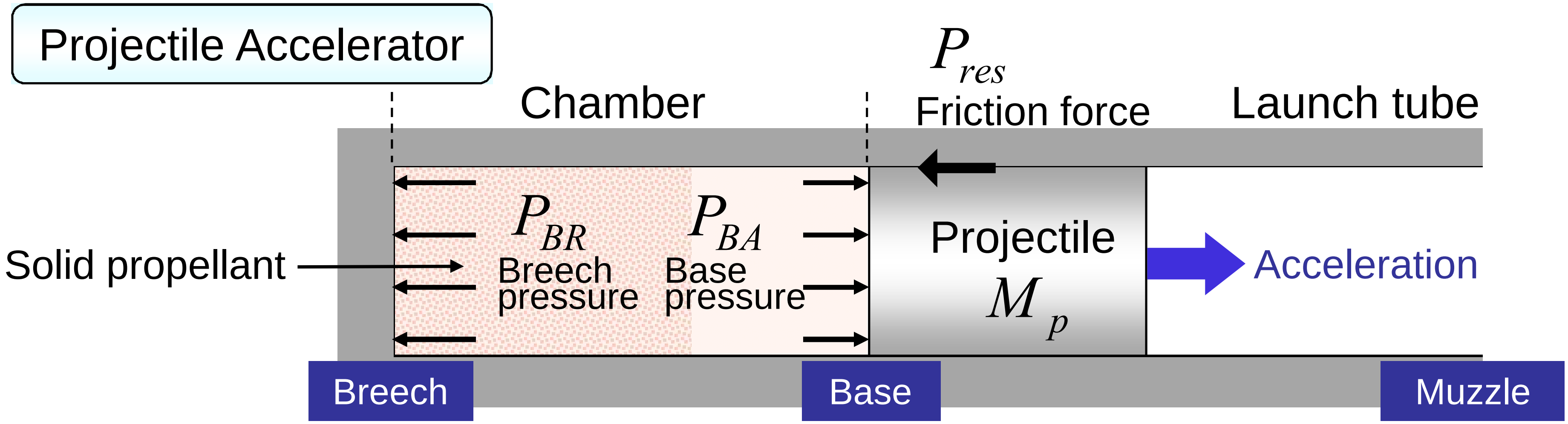
- Combustion gas and solid propellant coexist in the chamber.

- Chamber volume increases with the projectile movement.



...alysis Based on Interior Ballistics

Projectile Accelerator



Prediction of events in the accelerator is required.

Elements of accelerating process simulation by numerical analysis

- ❑ Solid/Gas two-phase flow
- ❑ Solid propellant combustion

  Propellant (Solid phase) → Combustion gas (Gas phase)
- ❑ Moving boundary problem

Objective

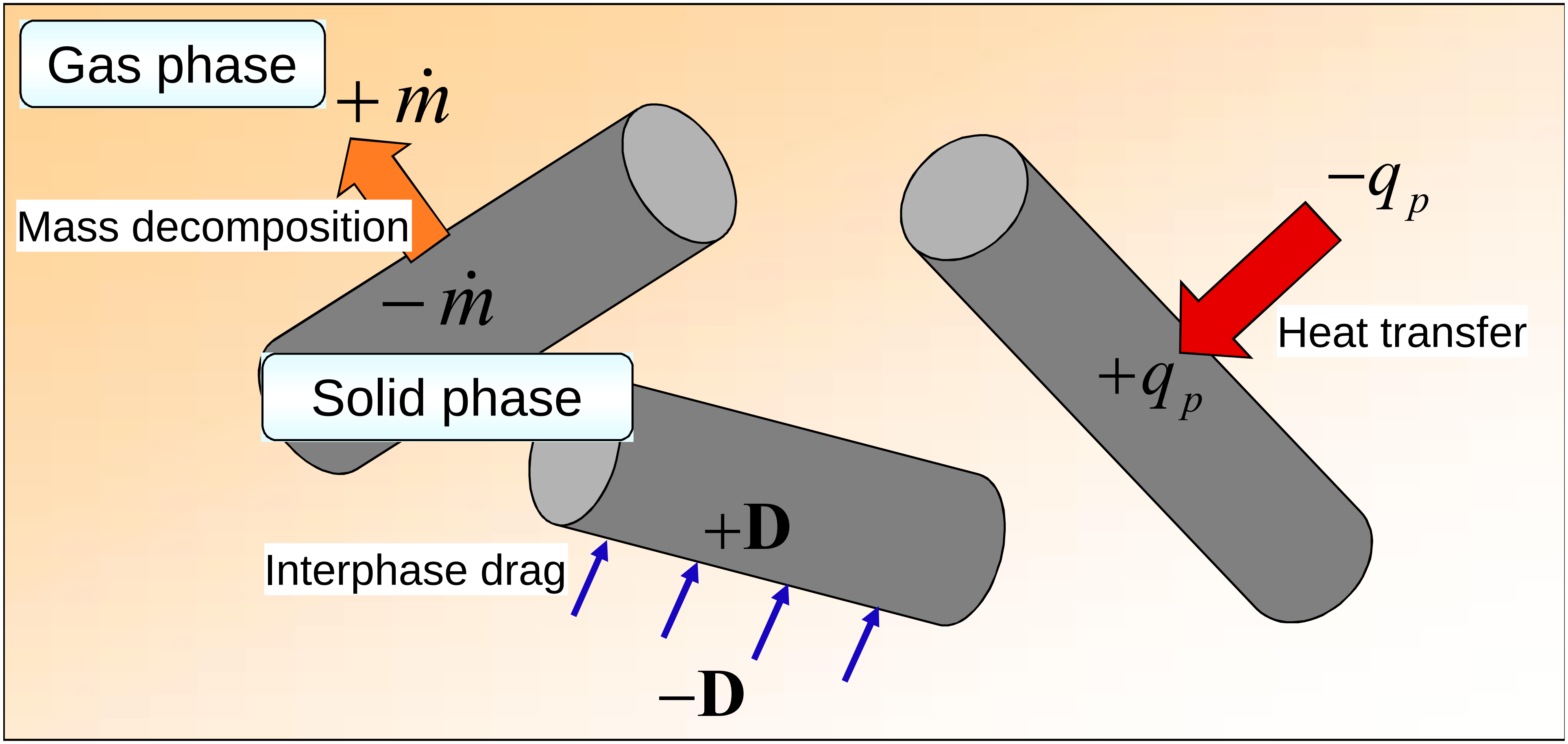
To simulate the process of accelerating a projectile by tubular solid propellant combustion in the 50mm projectile accelerator using the developed 2D axisymmetric two-phase flow code and the moving overlapped grid method.

- Simulation method is validated using experimental data.
  - Å Breech pressure history
  - Å Projectile velocity history
- Conditions of projectile mass Mp and propellant mass C are varied for the examination of those effects on the performance of gun system.
  - Å Maximum breech pressure
  - Å Projectile muzzle velocity and kinetic energy

Calculation Method for Interior Ballistics Simulation

- Two-phase Fluid Dynamics Code
- Modeling Tubular Propellant
- Modeling Projectile Movement

tion Between Two Phases



$$\dot{m} = \dot{m}(r) \qquad r = ap^n \qquad q_p = q_p\left(T_g - T_p\right)$$

$$\mathbf{D} = \mathbf{D}\left(\mathbf{u}_g - \mathbf{u}_p\right) \qquad T_p \geq T_{ignition} \rightarrow ignition$$

Governing Equations

Gas-phase

$$\frac{\partial}{\partial t}(\alpha\rho)+\nabla\cdot(\alpha\rho\mathbf{u})=\dot{m}+\dot{m}_{ig}$$

$$\frac{\partial}{\partial t}(\alpha\rho\mathbf{u})+\nabla\cdot(\alpha\rho\mathbf{u}\mathbf{u})=-\alpha\nabla p-\mathbf{D}+\dot{m}\mathbf{u}_p$$

$$\frac{\partial}{\partial t}(\alpha e)+\nabla\cdot\{\alpha(e+p)\mathbf{u}\}=-\mathbf{D}\cdot\mathbf{u}_p+\dot{m}\left(q+\frac{\mathbf{u}_p\cdot\mathbf{u}_p}{2}\right)+\dot{m}_{ig}q_{ig}-q_p$$

$$\begin{cases}\frac{\partial}{\partial t}(\alpha\rho Y_{pr})+\nabla\cdot(\alpha\rho Y_{pr}\mathbf{u})=\dot{m}\\ \frac{\partial}{\partial t}(\alpha\rho Y_{ig})+\nabla\cdot(\alpha\rho Y_{ig}\mathbf{u})=\dot{m}_{ig}\\ \frac{\partial}{\partial t}(\alpha\rho Y_{a})+\nabla\cdot(\alpha\rho Y_{a}\mathbf{u})=0\end{cases}$$

pr : propellant gas
ig : igniter gas
a : air

Solid-phase

$$m_{p,i}\frac{du_{p,i}}{dt}=(p_L-p_R)A_i+D_i-\dot{m}_i u_{p,i}$$

1D motion of *i*-th propellant

Gas-phase Ÿ Compressible fluid
Solid-phase Ÿ Constant density

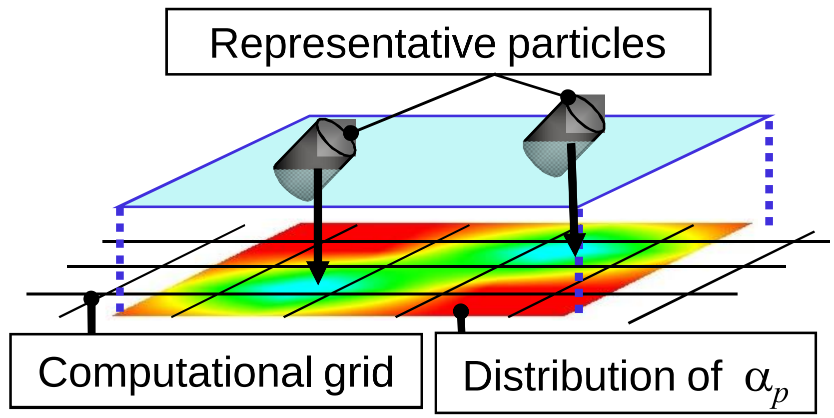
Computational volume is divided into the volume of gas and solid.

α : Volume fraction of gas-phase (porosity)

α_p : Volume fraction of solid-phase

$$\alpha=1-\alpha_p$$

The distribution of α_p is determined from the distribution of representative particles.



Governing Equations

Gas-phase

$$\frac{\partial}{\partial t}(\alpha\rho)+\nabla\cdot(\alpha\rho\mathbf{u})=\boxed{\dot{m}+\dot{m}_{ig}}$$

$$\frac{\partial}{\partial t}(\alpha\rho\mathbf{u})+\nabla\cdot(\alpha\rho\mathbf{u}\mathbf{u})=-\alpha\nabla p\boxed{-\mathbf{D}}\boxed{+\dot{m}\mathbf{u}_p}$$

$$\frac{\partial}{\partial t}(\alpha e)+\nabla\cdot\{\alpha(e+p)\mathbf{u}\}=\boxed{-\mathbf{D}\cdot\mathbf{u}_p}\boxed{+\dot{m}\left(q+\frac{\mathbf{u}_p\cdot\mathbf{u}_p}{2}\right)+\dot{m}_{ig}q_{ig}}\boxed{-q_p}$$

$$\begin{cases}\frac{\partial}{\partial t}(\alpha\rho Y_{pr})+\nabla\cdot(\alpha\rho Y_{pr}\mathbf{u})=\boxed{\dot{m}}\\ \frac{\partial}{\partial t}(\alpha\rho Y_{ig})+\nabla\cdot(\alpha\rho Y_{ig}\mathbf{u})=\boxed{\dot{m}_{ig}}\\ \frac{\partial}{\partial t}(\alpha\rho Y_{a})+\nabla\cdot(\alpha\rho Y_{a}\mathbf{u})=0\end{cases}$$

pr : propellant gas
ig : igniter gas
a : air

Solid-phase

$$m_{p,i}\frac{du_{p,i}}{dt}=(p_L-p_R)A_i\boxed{+D_i}\boxed{-\dot{m}_i u_{p,i}}$$

1D motion of *i*-th propellant

- Gas-phase components
  - Propellant combustion gas (pr)
  - Igniter combustion gas (ig)
  - Air (a)

- State equation for gas-phase

$$p=\frac{RT}{(1/\rho-b)}$$

b : Covolume

$\boxed{\dot{m}}$: Propellant mass decomposition rate

$\boxed{\dot{m}_{ig}}$: Igniter mass decomposition rate

$\boxed{\mathbf{D}}$: The interphase drag between two-phase

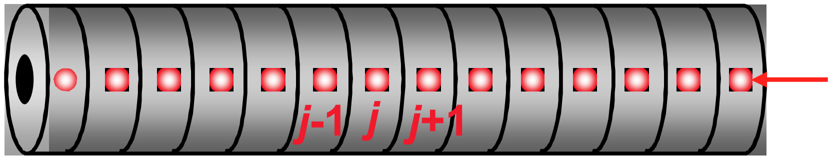
q : The combustion heat of propellant

q_{ig} : The combustion heat of igniter

$\boxed{q_p}$: Heat loss to solid phase

entative Particle Properties

Information of propellant geometry for ***j*-th representative particle**



At the end of each tubular propellant

Volume $$V_{p,j} = \left(\Delta L_{p,j} - \Delta u_j\right)\left\{\frac{\pi}{4}\left(D_p - 2\Delta u_j\right)^2 - \frac{\pi}{4}\left(d_p + 2\Delta u_j\right)^2\right\}$$

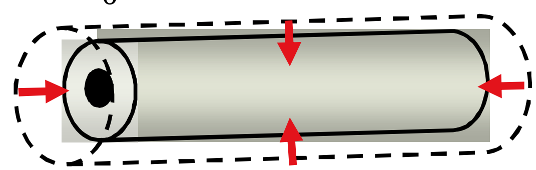
Surface area $$S_{p,j} = \pi\left(D_p - 2\Delta u_j\right)\left(\Delta L_p - \Delta u_j\right) + \pi\left(d_p + 2\Delta u_j\right)\left(\Delta L_{p,j} - \Delta u_j\right)$$
$$+\left\{\frac{\pi}{4}\left(D_p - 2\Delta u_j\right)^2 - \frac{\pi}{4}\left(d_p + 2\Delta u_j\right)^2\right\}$$

$\Delta L_{p,j}$: Divided length of tube

D_p : Outer diameter of tube

d_p : Inner diameter of tube

$\Delta u_j = \int_0^t r\,dt \qquad r = ap^n$



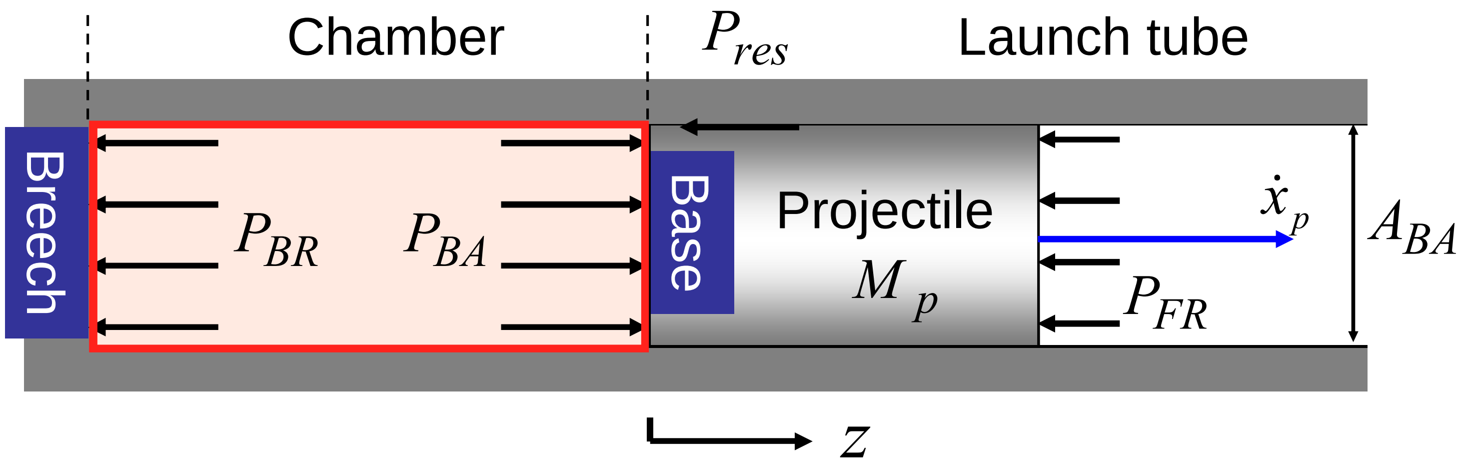
At the other position

Volume $$V_{p,j} = \Delta L_{p,j}\left\{\frac{\pi}{4}\left(D_p - 2\Delta u_j\right)^2 - \frac{\pi}{4}\left(d_p + 2\Delta u_j\right)^2\right\}$$

Surface area $$S_{p,j} = \pi\left(D_p - 2\Delta u_j\right)\Delta L_p + \pi\left(d_p + 2\Delta u_j\right)\Delta L_{p,j}$$

ectile Movement in Launch Tube

Kinetic model of projectile movement



P_{BR} : Breech pressure

P_{BA} : Base pressure

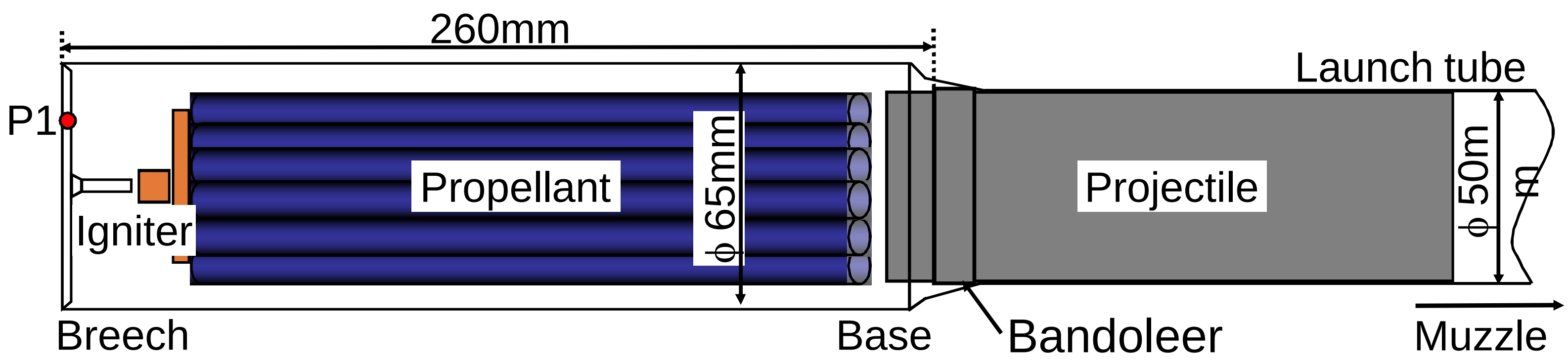
P_{res} : Resistive pressure

Projectile velocity $\dot{x}_p = \int_0^t \ddot{x}_p dt = \int_0^t \left(\frac{(P_{BA} - P_{FR} - P_{res}) A_{BA}}{M_p} \right) dt$

Interior Ballistics Simulation of 50mm Gun

Computational Model

Reproduction of the experiment of 50mm gun by NOF Corporation



The projectile velocity was recorded using an in-bore Doppler radar system.

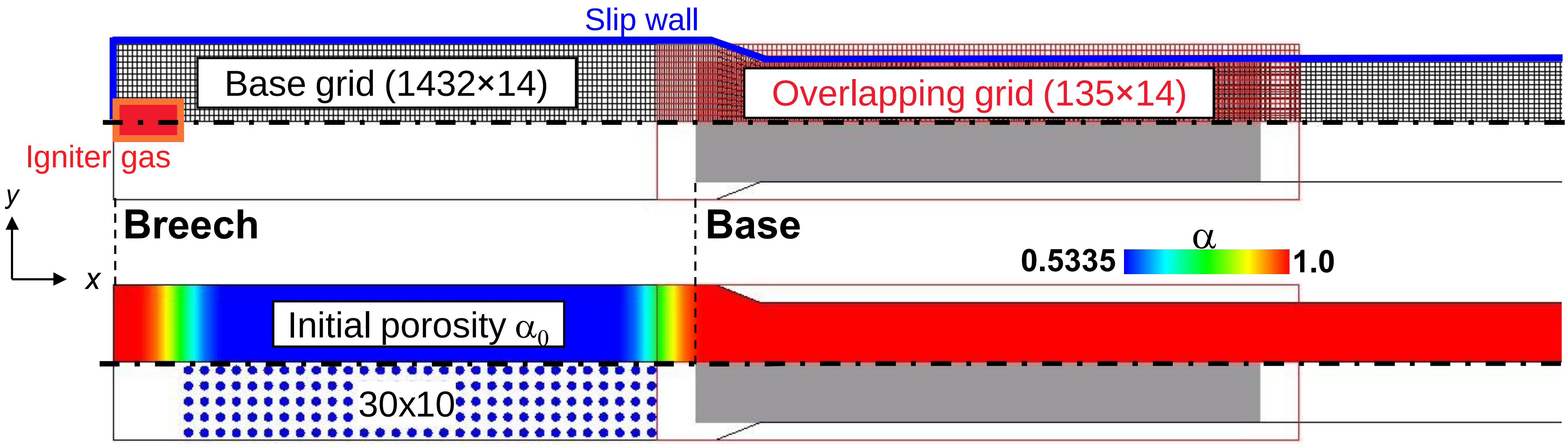
Computational data

Diameter of tube (mm)	50
Length of tube (mm)	3195
Projectile mass M_p (kg)	2.5, 3.5, 4.5
Propellant mass C (kg)	0.4, 0.5
Propellant type	Double-base
Shape of grain	Tubular (one hole)
Size of grain (mm)	ϕ6.35 x 200

Propellant properties

Adiabatic flame temperature T_0 (K)	3133
Impetus F (J/g)	1036
Specific heat ratio γ	1.232
Density ρ_p (kg/m^3)	1615
Covolume b (cm^3/kg)	993

Computational Setup



Calculation condition

Overlapping grid is movable

Wall condition : Adiabatic slip wall

Initial condition : 101kPa, 294K, γ=1.4

Calculation method

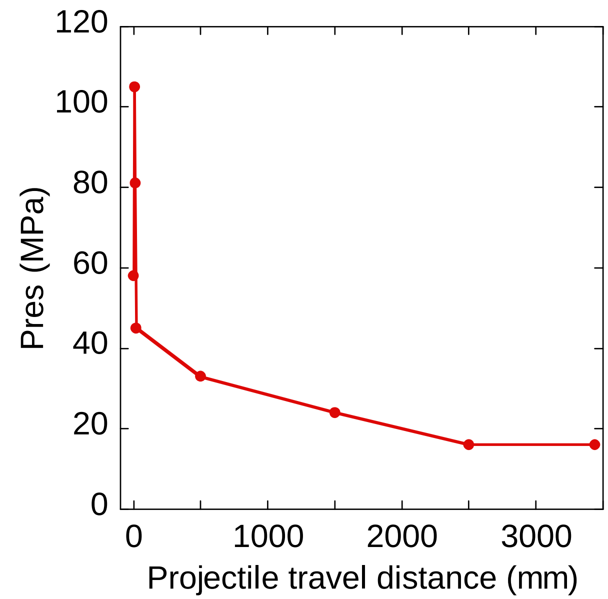
Discretization method of convection term

: SHUS (Shima and Jounouchi, 1995)

Time integration method

: 2-step Runge-Kutta method

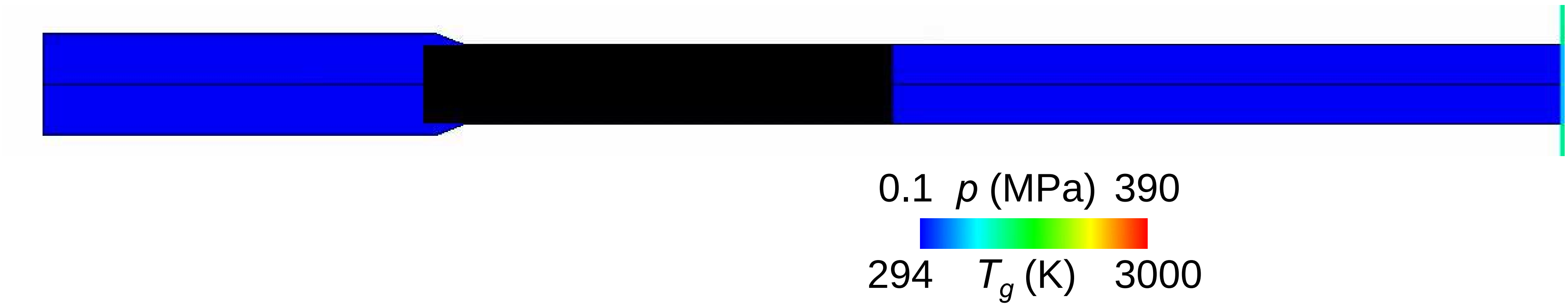
Resistive pressure P_{res}



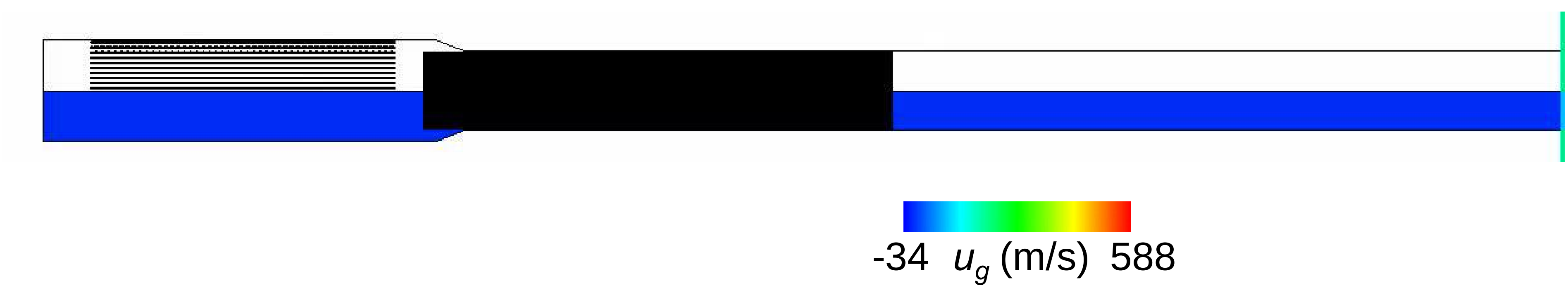
ccelerating Process

M_p=4.5kg and C=0.5kg

Pressure / gas temperature distribution

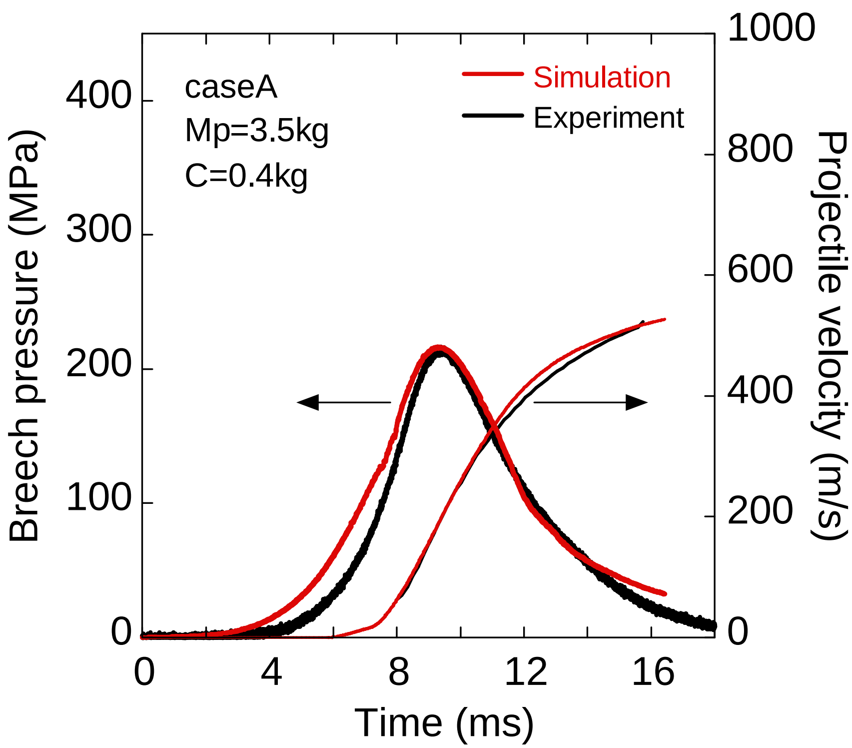


Propellant / gas velocity distribution

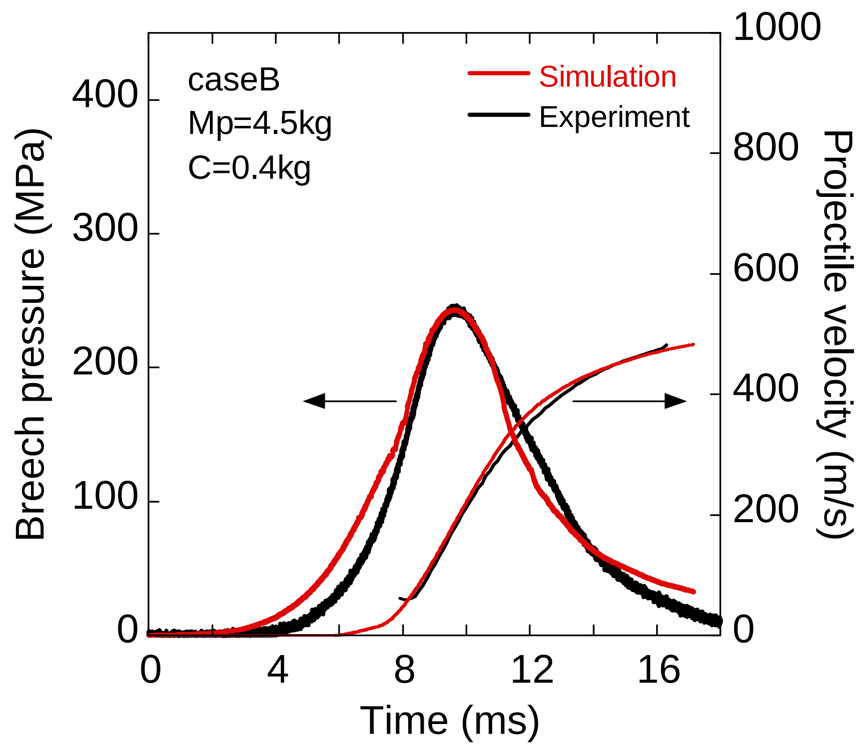


f Predicted Data with Experiment

Case A (M_p=3.5kg and C=0.4kg)



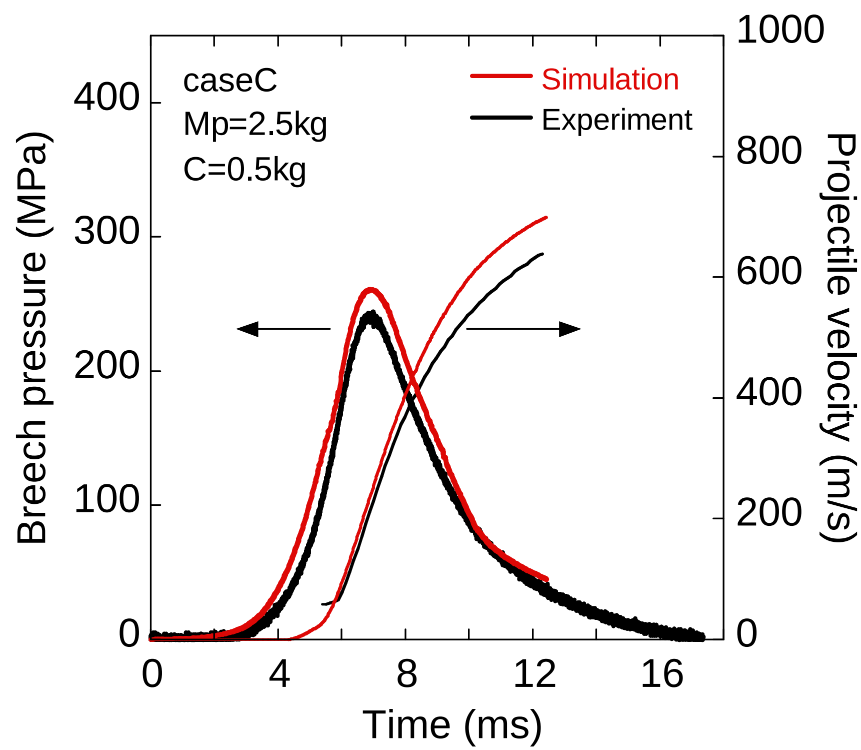
Case B (M_p=4.5kg and C=0.4kg)



- Predicted histories of the breech pressure and the projectile velocity are in good agreement with the experimental data in the each case.

f Predicted Data with Experiment

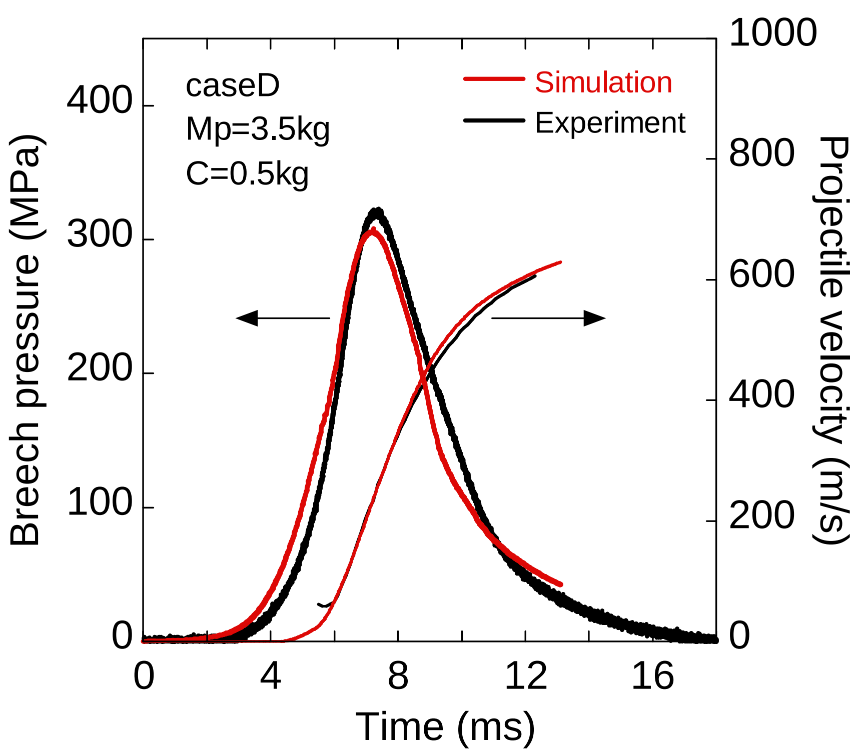
Case C (M_p=2.5kg and C=0.5kg)



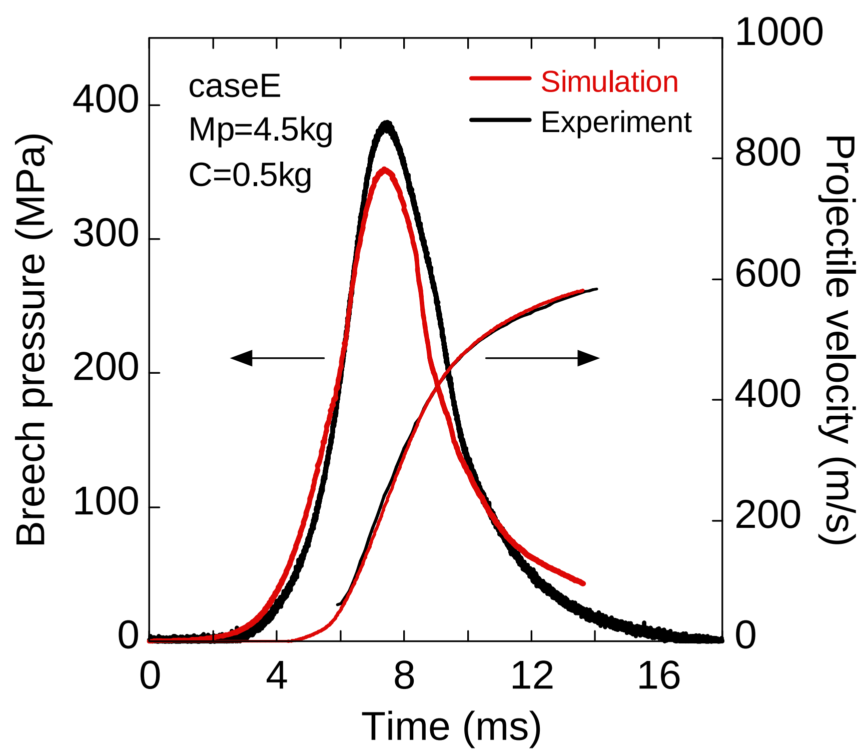
- Predicted breech pressure and projectile velocity are higher than the experimental data in this case.

f Predicted Data with Experiment

Case D (M_p=3.5kg and C=0.5kg)



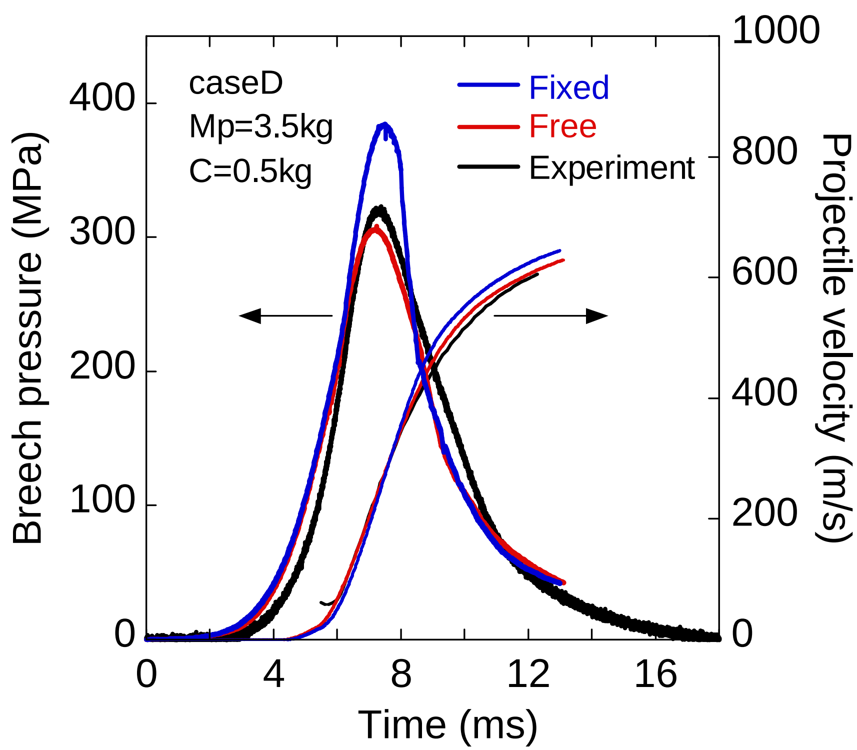
Case E (M_p=4.5kg and C=0.5kg)



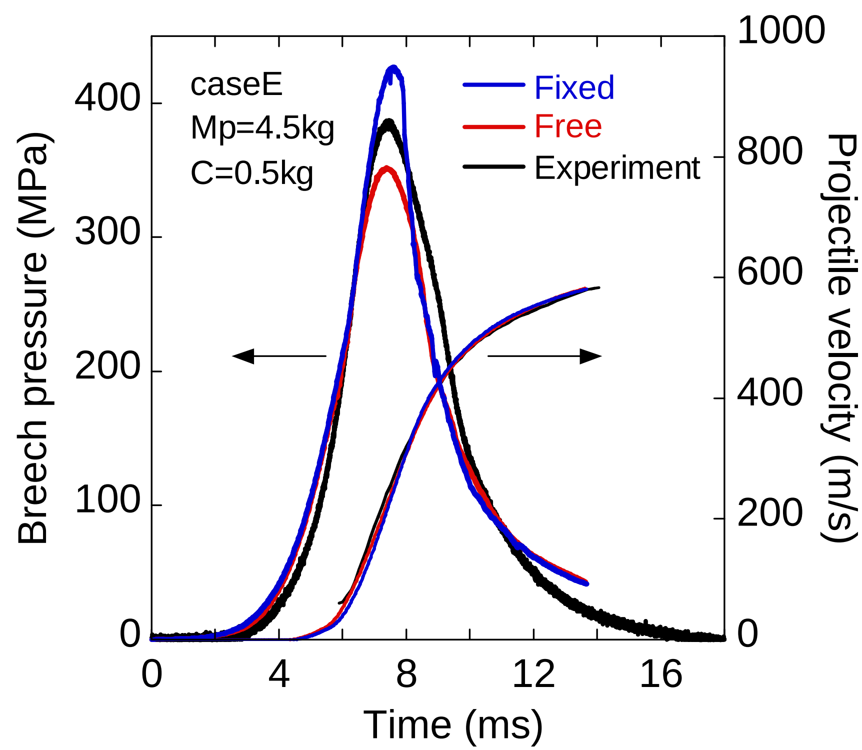
- ❑ Predicted histories of the breech pressure and the projectile velocity are in good agreement with the experimental data in the each case.

...nd Fixed Propellant Models

Case D (M_p=3.5kg and C=0.5kg)



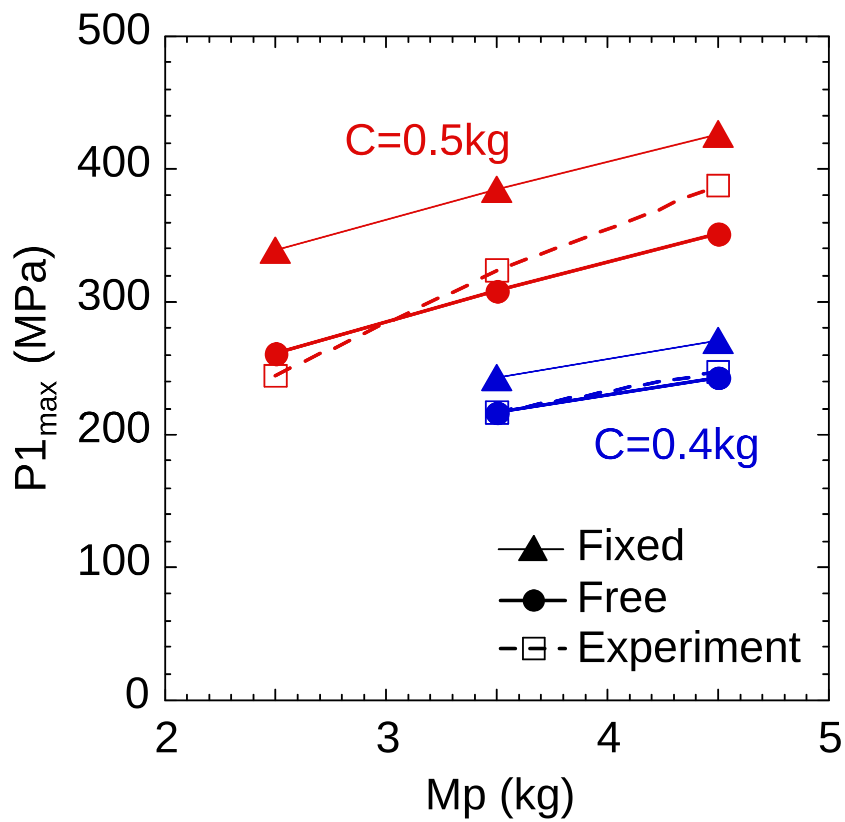
Case E (M_p=4.5kg and C=0.5kg)



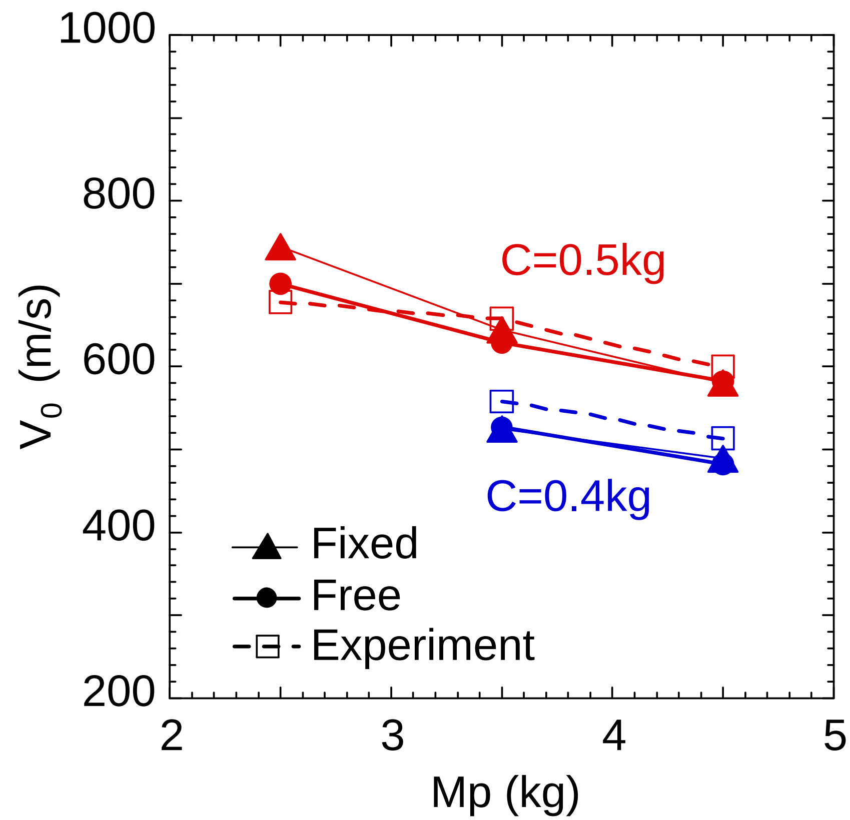
- If we use the fixed propellant model (without propellant movement), the predicted pressure becomes much higher than the free propellant model (with propellant movement).

d Fixed Propellant Models

Maximum Breech Pressure



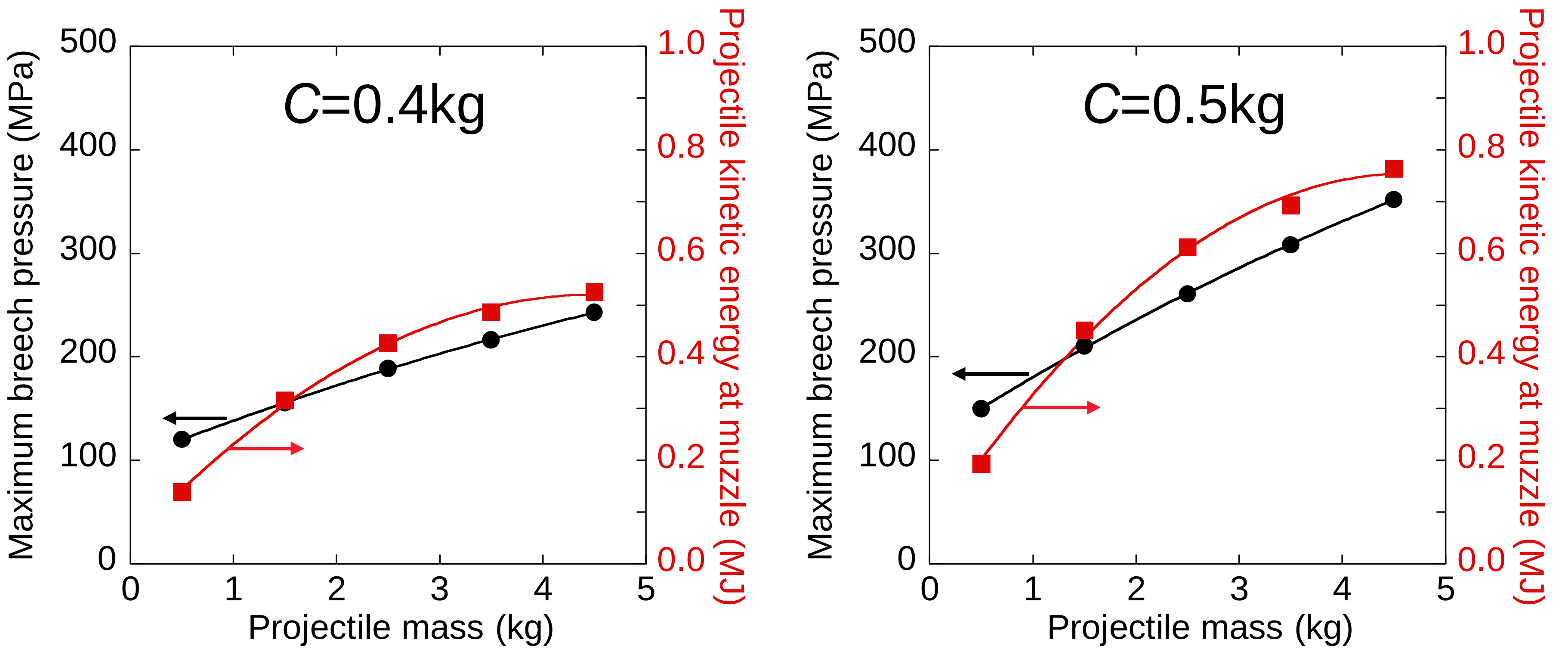
Muzzle Velocity



- The muzzle velocities of the two models were almost equivalent. However, the maximum breech pressure was overestimated by the **Fixed Model**, and the **Free Model** well reproduced the experimental maximum pressure.

ation of Projectile Mass

Simulated maximum breech pressure and projectile kinetic energy



- ❑ The maximum chamber pressure increases linearly whereas the projectile kinetic energy converges with the projectile mass Mp.

Conclusion

The processes of accelerating a projectile by tubular solid propellant combustion in the 50mm projectile launch system were simulated for various cases using the developed 2D two-phase flow code and the moving overlapped grid method.

- In the comparison between the predicted results and the experimental data of various Mp and C condition, the results of the simulation with propellant movement showed being in good agreement with the experimental results.

- There was trade-off relation between the chamber pressure suppression and the projectile kinetic energy improvement. However, the projectile kinetic energy at the muzzle converged with increasing the projectile mass Mp.

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